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On Be/X-ray binaries with an intermediate-mass black hole *

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Abstract We adopt the tidal truncation model proposed by Negueruela and Okazaki for Be/X-ray binaries to investigate the influence of intermediate-mass black holes (IMBHs) on Be-star disks. We show that the viscous decretion disks around Be stars are generally truncated ineffectively under the tidal force of IMBHs. Combining this with observations of Be/X-ray binaries, we suggest that Be/IMBH X-ray binaries may appear as recurrent luminous X-ray transients with quasi-periodic X-ray outbursts.

Key words: black hole physics — circumstellar matter — stars: emission-line, Be — X-rays: binaries

1 INTRODUCTION

Until recently, it has been generally believed that black holes (BHs) in nature appear in two broad mass ranges: stellar-mass ($M \sim 3 - 20\,M_\odot$) BHs, which are produced by the core collapse of massive stars, and supermassive ($M \sim 10^6 - 10^{10}\,M_\odot$) BHs, which are found in the centers of galaxies and are produced by a still uncertain combination of processes (e.g., Miller & Colbert 2004). It has long been suspected that intermediate-mass black holes (IMBHs), with mass $M \sim 10^2 - 10^4\,M_\odot$, may form in, for example, the centers of dense stellar clusters (e.g., Wyller 1970; Bahcall & Ostriker 1975). However, for many years there has been no convincing observational evidence for the existence of such objects. In the last decade, X-ray and optical observations revived this possibility. If such BHs do exist, especially in dense stellar clusters, they will have many implications, particularly for dynamical evolution of clusters and the generation of gravitational waves.

There are two types of observational data that suggest the possible existence of IMBHs. There are numerous ultraluminous X-ray sources (ULXs) discovered in nearby galaxies, which are not yet known to be associated with active galactic nuclei, and which have luminosities higher than that of an $M < 20\,M_\odot$ BH accreting at the Eddington limit (Fabbiano 1989, 2006, for reviews). Additionally, over the last decade, theoretical and observational evidence suggests that many star clusters may host IMBHs in their centers, just like galaxies do (Safonova & Stalin 2010; Chanamé et al. 2010, and references therein). N-body simulations have shown that for certain initial conditions, runaway merging of stars in dense star clusters as a result of collisions between young stars could lead to the formation of IMBHs (Portegies Zwart et al. 1999).

X-ray binaries provide the best sites to search for and investigate the properties of IMBHs. After its formation in a young, dense cluster, it is likely that an IMBH will soon form a binary by acquiring

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a companion star through dynamical interactions (Hopman et al. 2004; Blecha et al. 2006). Young massive stars, either isolated or in binary systems, tend to be in the centers of the clusters, and have a high probability of being captured by the IMBH to form a high-mass X-ray binary (HMXB) due to their large size. Accretion onto the BH via either Roche-lobe overflow or capture of the wind material from the massive star may power it to shine brightly in X-ray. The X-ray luminosities can be as high as $\gtrsim 10^{40}$ erg s^{-1}, comparable with those of ULXs (Li 2004). However, the stable X-ray lifetime is generally $\sim 10^6$ yr, much shorter than the main-sequence lifetime of the donor stars.

There may be cases for an IMBH to be a transient X-ray source when the companion star is still on the main-sequence. This happens if the companion is a Be star. Be stars are massive, early-type stars with a circumstellar disk, the origin of which is thought to be related to the rapid rotation of the star. Blecha et al. (2006) show that exchanges with binaries are the dominant processes for IMBHs to acquire companions in dense star clusters (the minimum binary fraction is larger than 11% within the core radius in Galactic open clusters, see Sollima et al. 2010). Considering the fact that the fraction of Be stars to B stars ranges from 0.16 in our Galaxy to 0.39 in the Small Magellanic Cloud (Maeder et al. 1999), and that roughly two-thirds of HMXBs are Be/X-ray binaries (Ziolkowski 2002), a considerable fraction of the binary companions acquired by IMBHs may be Be stars. Since the resulting binary orbits are generally wide (with orbital periods > 10 d, Blecha et al. 2006), the Be stars may keep rapid rotation for a sufficiently long time, as tidal damping on the stellar spin will occur on a timescale $>$ a few 10^7 yr (cf. Hurley et al. 2002).

Currently known Be/X-ray binaries in the Galaxy and the Magellanic Clouds all contain an accreting neutron star. While a small fraction of Be/X-ray binaries are persistent X-ray sources (see Reig & Roche 1999), which display low luminosity ($L_\mathrm{X} \sim 10^{34}$ erg s^{-1}) at a relatively constant level, most known Be/X-ray binaries are transients, showing two different types of outbursts: type I X-ray outbursts of moderate intensity ($L_\mathrm{X} \sim 10^{36}$–$10^{37}$ erg s^{-1}) occurring in series separated by the orbital period, generally (but not always) close to the time of periastron passage of the neutron star, and type II X-ray outbursts ($L_\mathrm{X} \gtrsim 10^{37}$ erg s^{-1}) lasting for several weeks or even months. Generally, type II outbursts start shortly after periastron passage, but do not show any other correlation with orbital parameters (Finger & Prince 1997). Recently, theoretical work on disk truncation in Be/X-ray binaries (Okazaki & Negueruela 2001; Okazaki et al. 2002) was invoked to explain the X-ray outbursts in Be/X-ray binaries and has had considerable success in its application to several systems (Okazaki & Negueruela 2001), especially 4U 0115+63/V635 Cas (Negueruela & Okazaki 2001) and A0535+26 (Haigh et al. 2004). The key idea is as follows. The neutron star exerts a negative tidal torque on the viscous decretion disk of the Be star, diminishing the action of the viscous torque outside some critical radius and thus resulting in the truncation of the disk. The disk matter will then accumulate in the outer rings of the disk until the truncation is overcome by the effects of global one-armed oscillations, disk warping, etc. The subsequent sudden infall of high-density disk matter onto the neutron star causes type II X-ray outbursts. During the episodes between the outbursts, the neutron star could hardly be observed because of its low mass accretion rate or the propeller effect. On the other hand, if the tidal truncation was not very efficient and the disk can extend beyond the Roche lobe of the Be star at periastron, the matter will be accreted onto the neutron star during the periastron passage, resulting in (quasi-)periodic type I bursts.

It is interesting to note that there are no acknowledged Be/BH X-ray binaries. The lack of observed Be/BH X-ray binaries might be due to the low birthrate of such objects (e.g. Raguzova & Lipunov 1999). Alternatively, Zhang et al. (2004) have shown that the viscous decretion disk around a Be star can be truncated very effectively by a surrounding BH, so that most of the Be/BH binaries tend to be transient systems with a very long quiescent state. However, how the Be star disk is influenced by an IMBH is still not clear. In this paper, we extend the application of the tidal truncation model to investigate the tidal effect of IMBHs on Be-star disks. The model and the necessary parameters are briefly described in Section 2. The numerically calculated results are shown in Section 3. The physical implications are discussed in Section 4.

2 MODEL

There is overwhelming evidence that the disks around Be stars are in quasi-Keplerian rotation (see Hanuschik et al. 1996; Hummel & Hanuschik 1997) and that the bulk outflow velocities in the disks are smaller than a few km s^{-1} (Hanuschik 2000). The disks surrounding Be stars are generally thought to be viscous decretion disks (Lee et al. 1991), in which angular momentum is transferred from the central star by some mechanism still to be determined to the inner edge of the disk, increasing its angular velocity to Keplerian. Viscosity operates in a way opposite to an accretion disk, and conducts material outwards. Material in the disk moves in quasi-Keplerian orbits and the radial velocity component is highly subsonic until the material reaches a distance much larger than the line-emitting regions (Okazaki 2001). Negueruela & Okazaki (2001) have combined the viscous decretion disk model and the tidal truncation model (Artymowicz & Lubow 1994) for the gravitational interaction of an eccentric binary system with circumstellar or circumbinary disks to explain the outburst phenomena in Be/X-ray binaries.

Following Negueruela & Okazaki (2001), we consider the picture of the Be/X-ray binary in which the compact star of mass M_{X} moves around a Be star of mass M_* and radius R_* in an orbit of eccentricity e and period P_{orb}. For simplicity, the Be disk is assumed to be isothermal, and Shakura-Sunyaev's viscosity prescription is adopted. In such a disk, angular momentum is added to the disk by the viscous torque T_{vis}, whereas it is removed from the disk by the resonant torque T_{res} exerted by the compact star, which becomes non-zero only at radii where the ratio between the angular frequency of disk rotation and the angular frequency of the mean binary motion is a rational number. As a result, the disk decretes outward owing to the transfer of angular momentum by viscosity until T_{res} becomes larger than T_{vis} at a resonance radius. Therefore, the criterion for the disk truncation at a given resonance radius r_{tr} is written as

$$T_{\mathrm{vis}} + T_{\mathrm{res}} \leq 0, \tag{1}$$

where T_{res} is dominated by the torque of the inner Lindblad resonance $T_{\mathrm{res}} \simeq \sum_{ml}(T_{ml})_{\mathrm{ILR}}$. For near-Keplerian disks and inner Lindblad resonances, the expression of viscosity and resonance torques is given by equations (8) and (11) in Okazaki & Negueruela (2001). The above truncation criterion can be approximated as[1]

$$\alpha\left(\frac{H}{r}\right)^2 \leq \frac{\pi a^2 \sum_{ml}[m/(m-1)](\lambda+2m)^2\phi_{ml}^2}{9(GM_*)^2(1+q)^{2/3}n^{4/3}}, \tag{2}$$

at the radius of the inner Lindblad resonance

$$r_{\mathrm{tr}} = n^{-2/3}(1+q)^{-1/3}a = n^{-2/3}[GM_*/(2\pi/P_{\mathrm{orb}})^2]^{1/3}, \tag{3}$$

where α is the Shakura-Sunyaev viscosity parameter, a the semimajor axis of the binary orbit, $q = M_{\mathrm{X}}/M_*$, $\lambda = (r/\phi_{ml})(\mathrm{d}\phi_{ml}/\mathrm{d}r)$, and H the vertical scale-height of the disk given by

$$\frac{H}{r} = \frac{c_{\mathrm{s}}}{V_{\mathrm{K}}(R_*)}\left(\frac{r}{R_*}\right)^{1/2} \tag{4}$$

for isothermal disks. Here, c_{s} is the isothermal sound speed and $V_{\mathrm{K}}(R_*)$ is the Keplerian velocity at the stellar surface. In our calculation, $c_{\mathrm{s}}/V_{\mathrm{K}}(R_*) \simeq 4.1 \times 10^{-2}(T_{\mathrm{d}}/T_{\mathrm{eff}})^{1/2}$ is assumed as in Okazaki & Negueruela (2001), where the disk temperature T_{d} is about 1/2 of the effective temperature T_{eff} of the Be star. We adopt the mass-radius relation $R_*/R_\odot \simeq (M_*/M_\odot)^{0.8}$ to estimate the radius R_* of the Be star.

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[1] Note that there is a typo in eq. (2) in Zhang et al. (2004), which is corrected here.

The potential component ϕ_{ml} in Equation (2) is calculated by using Goldreich & Tremaine's (1979, 1980) torque formula, after decomposing the binary potential into a double Fourier series. For the inner Lindblad resonance, it can be expressed as

$$\phi_{ml} = -\frac{GM_{\rm X}}{a}\frac{1}{\pi}\int_0^{\pi} df\left\{\frac{(1-e^2)^{1/2}}{1+e\cos f}\cos[mf-n(m-1)M(f)]b^m_{1/2}(r/r_2(f))\right\}, \tag{5}$$

where

$$b^m_{1/2}(\beta) = \frac{2}{\pi}\int_0^{\pi}\frac{\cos m\varphi}{(1-2\beta\cos\varphi+\beta^2)^{1/2}}d\varphi \tag{6}$$

is the Laplace coefficient with argument $\beta = r/r_2$, and $r_2 = a(1-e^2)/(1+e\cos f)$ is the distance of the compact star from the donor star. We refer to Negueruela & Okazaki (2001) and Zhang et al. (2004) for a detailed procedure of solving the integration in ϕ_{ml}.

We sum the inner Lindblad resonance torque in Equation (2) from $m = 2$ to the value at which the component is 3 orders smaller than that of $m = 2$, since the higher order components contribute little.

The efficient truncation is defined as (Okazaki & Negueruela 2001)

$$\gamma \equiv \left(\frac{\tau_{\rm drift}}{P_{\rm orb}}\right)_{\rm min} \sim \frac{\Delta r}{0.1c_{\rm s}P_{\rm orb}} > 1, \tag{7}$$

where $\Delta r = d_{L1} - r_{\rm tr}$ is the gap between $r_{\rm tr}$ and the inner Lagrangian point d_{L1}, and $d_{L1} = (0.500 - 0.227\log q)a(1-e)$ (Frank, King & Raines 2002).

3 RESULTS

To compare the results with those in Zhang et al. (2004), we chose similar values of the binary parameters in our calculation as in Zhang et al. (2004), i.e., $M_* = 6$, 15, and $20\,M_\odot$, $P_{\rm orb} = 5$, 30, 100, and 250 d, and $e = 0.01$, 0.05, 0.1, 0.3, and 0.5. The BH masses are taken to be $M_{\rm X} = 10$, 100, and $1000\,M_\odot$. The viscous parameter α is set to be 0.1 and 0.3, as suggested by observations of dwarf novae and soft X-ray transients (King, Pringle & Livio 2007).

In the cases of $M_{\rm X} = 10$ and $100\,M_\odot$, the calculated values of the truncation efficiency criterion γ are shown against the eccentricity in Figures 1, 2, and 3 with $M_* = 6$, 15, and $20\,M_\odot$, respectively. The data are grouped by different $P_{\rm orb}$. It is seen that the features of γ are generally similar between the cases of $M_{\rm X} = 10$ and $100\,M_\odot$, i.e., more efficient truncation occurs when either of the following conditions is satisfied: (1) the orbital period is smaller, (2) the viscosity parameter is smaller, or (3) the Be stars are more massive. Considering the fact that IMBH X-ray binaries are thought to be wide systems, these figures suggest that disk truncation in these systems is more likely to be inefficient.

The above conclusion is reinforced by the calculated results with $M_{\rm X} = 1000\,M_\odot$. In this case, we find that the values of the truncation efficiency γ are generally < 0. The negative values represent ineffective truncation with $r_{\rm tr} > r_{\rm L1}$, and thus have no physical meaning. Only in limited cases we have $\gamma > 0$ but all < 1. The result with $M_* = 20\,M_\odot$ and $P_{\rm orb} = 5\,$d is shown in Figure 4 as an example. Combining the above results, we conclude that disk truncation in Be/IMBH X-ray binaries are likely to be ineffective.

4 DISCUSSION

Zhang et al. (2004) applied the tidal truncation model proposed by Negueruela & Okazaki (2001) to Be X-ray binaries with stellar-mass BHs, to investigate the dependence of truncation efficiency on some basic binary parameters such as stellar mass, viscosity, orbital period, and eccentricity. Their results not only confirmed the prediction that low viscosity and small eccentricity would lead to

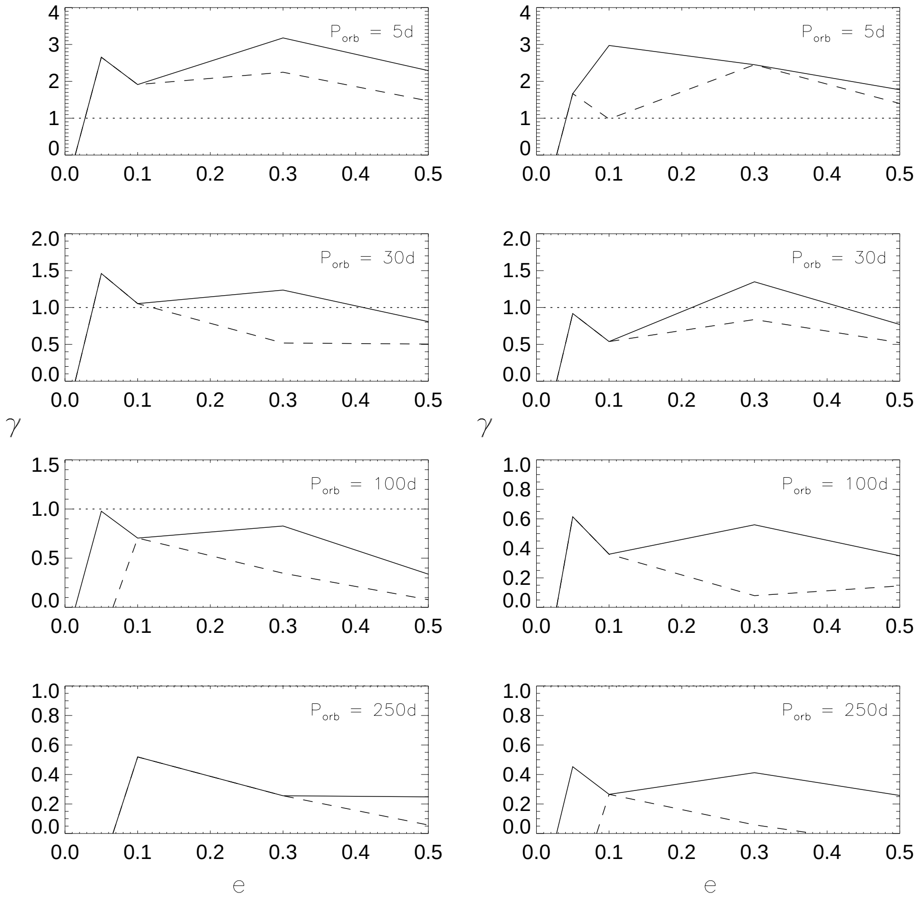

Fig. 1 Eccentricity dependence of the truncation efficiency γ for Be/BH binaries ($M_{\rm X} = 10\,M_{\odot}$, *left*) and Be/IMBH binaries ($M_{\rm X} = 100\,M_{\odot}$, *right*) with Be star mass $M_{*} = 6\,M_{\odot}$. Solid and dashed lines are obtained with the disk viscosity parameter $\alpha = 0.1$ and 0.3, respectively. Dotted lines of $\gamma = 1$ are drawn for comparison.

effective Be disk truncation (Okazaki & Negueruela 2001), but also showed that the most effective truncation would occur in relatively narrow systems (Zhang et al. 2004). We extend their work to investigate the influence of IMBHs on the Be-star disks. For the initial parameters of the binaries, we refer to the numerical simulations in Blecha et al. (2006). They assumed that a $50 - 500\,M_{\odot}$ IMBH has formed through runaway growth of massive stars in dense, young ($\sim 100\,$Myr) stellar clusters, and modeled interactions of the IMBH with single and binary stars, as well as single-binary and binary-binary interactions. They found that the formed binary parameters are distributed in the following range for a $100\,M_{\odot}$ BH: $10^2\,R_{\odot} < a < 10^4\,R_{\odot}$ and $M_{\odot} < M_{*} < 10\,M_{\odot}$, corresponding to $P_{\rm orb} \sim 30 - 250\,$d. Eccentricities were found to follow the initial thermal distribution, which favors higher values. Our calculations show that the high BH mass ($M_{\rm X} \gtrsim$ 100–1000 $M_{\odot}$) leads to a highly ineffective tidal truncation, especially for wide systems. This means that the disk wind material may be accreted onto the BH during the periastron passage, resulting in (qusi-)periodic type I outbursts.

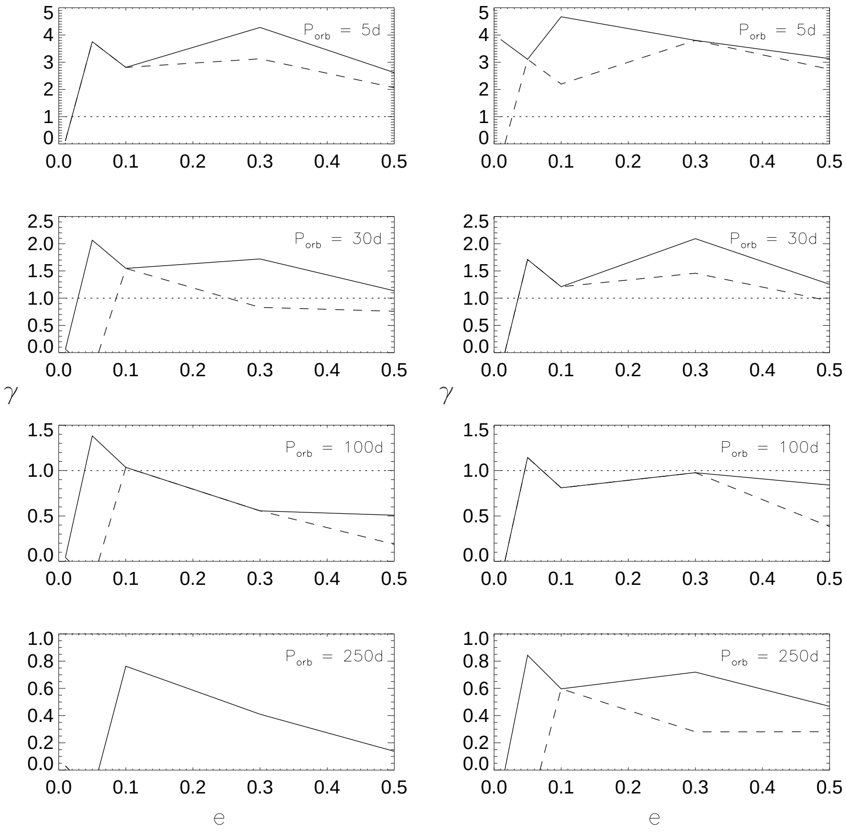

Fig. 2 Same as Fig. 1, but with $M_* = 15\,M_\odot$.

For normal Be X-ray binaries, the observed X-ray luminosities during type I outbursts are up to $\sim 10^{37}$ erg s^{-1}. As the mass of an IMBH is much higher than a neutron star, the outbursts of Be/IMBH binaries might show some different characteristics from normal Be/X-ray binaries. The Eddington luminosities of $M_{\rm X} \sim 100 - 1000\,M_\odot$ IMBHs, given by

$$L_{\rm Edd} \simeq 1.3 \times 10^{38} \left(\frac{M_{\rm X}}{M_\odot}\right) {\rm erg\ s}^{-1}, \tag{8}$$

fall in the range $\sim 10^{40} - 10^{41}$ erg s^{-1}. This means that, if the accretion rates to an IMBH during outbursts are similar in magnitude to those in normal Be/X-ray binaries, the ratio of the accretion rate to the Eddington accretion rate would be $< 10^{-3}$, so that the accretion disk around the IMBH would be in the form of an advection-dominated accretion flow (Narayan & Yi 1994). In this case, since the radiative efficiency is considerably lower than in a standard, thin disk (Esin et al. 1997), the actual luminosity may be $\lesssim 10^{36}$ erg s^{-1}, and the spectrum is expected to resemble that of the low/hard state of Galactic BH X-ray binaries. It would be difficult to detect such faint, hard X-ray outbursts in external galaxies.

The actual luminosities of IMBHs could be much higher than the above values, due to the following reasons. Firstly, Tout & Eggleton (1988) suggested that the stellar wind mass loss may be tidally enhanced by a factor of a few 10^2, if there is a moderately close binary companion. This

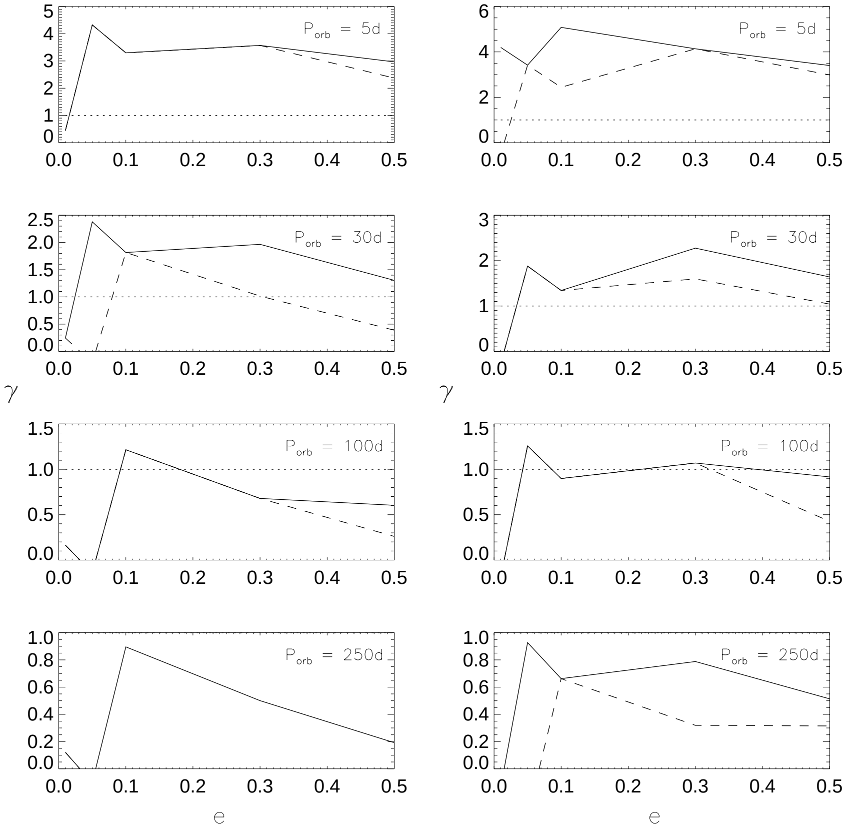

Fig. 3 Same as Fig. 1, but with $M_* = 20\,M_\odot$.

enhancement, if realistic, should be even higher when the companion is replaced by an IMBH. Secondly, under the condition of the same donor mass and binary separation, the accretion rate onto an IMBH is likely to be higher than a neutron star. Attempts at modeling the X-ray luminosities of Be/X-ray transients during outbursts have made use of a simple wind accretion model. The rate of mass capture by the compact star from the stellar wind of the Be companion can be roughly evaluated as

$$\dot{M}_{\rm X}(a) \simeq \pi R_{\rm eff}^2 \rho(a) V_{\rm rel}(a), \tag{9}$$

where $R_{\rm eff} = 2GM_{\rm X}/V_{\rm rel}^2$ is the effective accretion radius, ρ the plasma density in the wind, and $V_{\rm rel}$ the relative velocity between the compact star and the surrounding gas. Usually, $R_{\rm eff}$ is larger than the binary separation for Be/X-ray binaries (Okazaki 2001), so a crude way around this problem is to consider that the radius of the effective Roche lobe of the compact star $R_{\rm L,X}$ should be used instead (Ikhnasov 2001). This yields the ratio of the accretion rates onto an IMBH and a neutron star,

$$\frac{\dot{M}_{\rm IMBH}}{\dot{M}_{\rm NS}} \sim \left(\frac{M_{\rm IMBH} + M_*}{M_{\rm NS} + M_*}\right)^{1/2} \left(\frac{R_{\rm L,IMBH}}{R_{\rm L,NS}}\right)^2 \sim 100, \tag{10}$$

with $M_{\rm NS} = 1\,M_\odot$, $M_{\rm IMBH} = 100 - 1000\,M_\odot$, and $M_* = 10\,M_\odot$. Accordingly, the X-ray luminosity during type I outbursts may increase to $L_{\rm X} \gtrsim 10^{38} - 10^{39}$ erg s^{-1}, which means that the Be/IMBH binaries might appear as recurrent X-ray binaries with (quasi-)stable periods. The X-ray

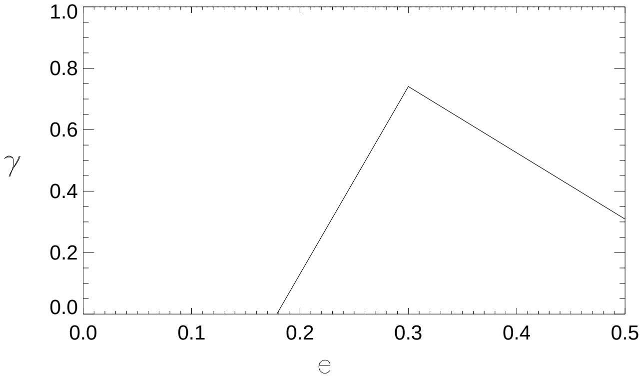

Fig. 4 Eccentricity dependence of the truncation efficiency γ for $M_{\rm X} = 1000\,M_\odot$ Be/IMBH binaries with Be star mass $M_* = 20\,M_\odot$ and $P_{\rm orb}$=5 d.

spectral state could be described as the low/hard state or the intermediate state (Esin et al. 1997; Done & Gierlinski 2003), depending on the mass of the IMBH.

Winter et al. (2006) conducted an archival *XMM-Newton* study of the bright X-ray point sources in 32 nearby galaxies. From a list of approximately 100 point sources, they found that there exists a population of objects whose X-ray spectral properties closely match the low/hard-state spectra of Galactic BHs, but whose luminosities lie in the range of $\sim\, 2\times10^{38}-1\times10^{40}$ erg $\rm s^{-1}$. A fraction of the X-ray sources have shown strong long-term flux variability (Terashima & Wilson 2004; Dewangan et al. 2004, 2005), or have appeared to be transients (Roberts et al. 2002; Isobe et al. 2008). Due to the sparse monitoring, the nature of these sources is still unclear. If future observations can identify quasi-periodic recurrent outbursts and/or their optical counterparts as Be stars in some of the sources, they may be good candidates for Be/IMBH binaries.

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